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A DIGITAL SIMULATION OF THE MFTF POWER SUPPLY SYSTEM USING EMTP*

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Summary

The power supply system for MFTF will consist of twenty-four sets of accel, arc, and filament power supplies. The system will be fed from a common source and split into sets of two for the accel supplies and sets of four for the arc and filament supplies. This paper describes the simulation of this system and the EMTP code that was used. Interactions between power supplies during turn on that are due to common system impedances are studied, and a description of Transient Analysis of Control Systems (TACS) control is presented. The system harmonic content found by EMTP is discussed. The paper concludes with a brief discussion of an accel crowbar simulation.

Introduction

A power supply system the size and complexity of MFTF warrants computer modeling. There are many electronics codes available, each one having its merits and limitations. After a search and recommendation by an independent agent, we chose the Electromagnetic Transients Program (EMTP) to model the system. This code is available to all MFE computer users by contacting the author.

EMTP

EMTP was originated at the Bonnevile Power Administration (BPA) in the mid-1960's to model some of their problems with the high-voltage direct-current (HVDC) intertie. Throughout the years, BPA has given the code freely to anyone requesting it. It has become a standard among utilities and consulting firms, and cooperation among all users has led to today's developed code.

Since its inception, EMTP has had about 50 different authors who added to or refined the features that are in today's version. Consequently, the code is something of a programmer's nightmare, with 45,000 lines of computation code and another 9,000 lines of housekeeping. The Fortran source is not well documented, and the user's manual can be hard to follow, (in places, information on a particular subject is scattered throughout). New users have some trouble getting started; however, the output is extremely well documented, and a coding error is usually easily corrected.

EMTP was designed around three-phase power systems. The standard elements include the transformer, the distributed-parameter transmission line, the frequency dependent transmission line, the nonlinear resistance and inductance, lightning arrestors, time-varying resistors, ordinary and controlled switches, and diodes. Voltage and current sources must have one terminal connected to ground. Each node may have at most one switch or diode connected to it, unless that node is ground. An initial conditions file can be created at the end of a run to be included as input to a subsequent run, but not all elements -- most notably the saturable transformer -- can accept initial conditions. These and other limitations will soon be corrected in a new version of EMTP to be released by BPA. BPA maintains the code for thirteen different machines. EMTP is available to MFE users on the CDC 7600; however, this is an older version and is not as updated as the CRAY version, which allows the use of Transient Analysis of Control Systems (TACS), and requires about 2-1/2 times less computing time.

Unlike some codes, EMTP uses a fixed time interval between computation points. The solution method uses the trapezoidal rule of integration, which is a simple approximation and is fairly stable for most applications, although it is not as accurate and elegant as other methods used in other codes. Experience has shown that when the simulation is entirely 60 Hz, a 50 μsec time step is adequate, and a 5 μsec step will usually suffice for a rectifier.

One of EMTP's strong points is the TACS feature, which enables a user to control the electronic network by monitoring network voltages and currents and processing these signals to become control signals for the network. The processing features include the following:

- Transfer functions in "s,"
- Summers,
- Static and dynamic limiters,
- Algebraic and logical operators,
- All functions of the Fortran library,
- Special devices (which include frequency sensors, relays, level-triggers, transport delays, digitizers, point-by-point nonlinearities, and time-sequenced switches).

Although TACS is somewhat difficult to master, its applications are limited only by the imagination of the user. Indeed, TACS has been used to study subsynchronous resonance problems of various synchronous generators.

MFTF System

Circuit Schematic

Shown in Fig. 1 is a one-line diagram of the MFTF power supply system. The numbers near the impedances call for some explanation. AC/12 signifies one twelfth the impedance of an accel supply; A,F/12 represents one twelfth the impedance of an arc supply and a filament supply, or 12 arc and 12 filament supplies in parallel. Because there are two 13.8 kV/480 V circuits on each 230/13.8 kV transformer secondary, -- each powering six arc and six filament supplies -- the impedance of the 13.8 kV/480 V transformer appears as one half the impedance of one transformer, and all 12 arc and filament supplies can be represented as being in parallel. Using this paralleling technique on the symmetry of the system results in Fig. 2. Due to problems arising from the machine roundoff error, the impedances of the system are multiplied by twenty-four, after the 24 accels are split into two groups of 12, spaced 15^{0} degrees

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apart to yield the 24 pulse system shown in Fig. 3. The characteristics of the system have not changed, and the voltage drops at the common busses are unaltered. However, care must be taken when interpreting the current at various points in the system. This scheme, with only two accels, one arc, and one filament power supply, can be used to determine the interactions of the system during turn-on.

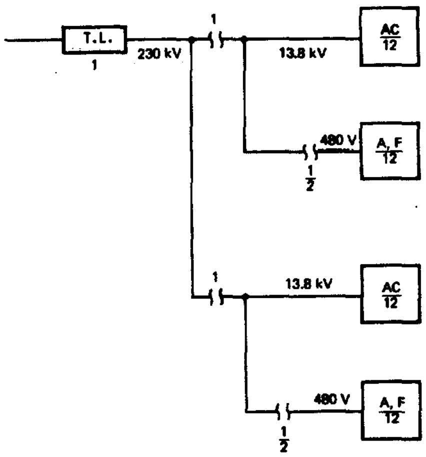

Fig. 1

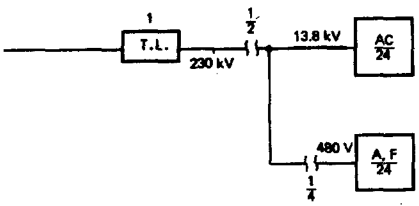

Fig. 2

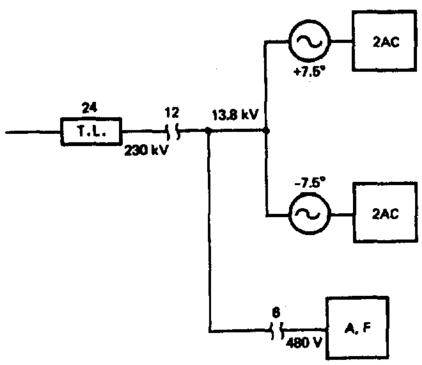

Fig. 3

Circuit Operation

Originally it was thought to operate the power supplies by letting the arc and filament supplies stabilize and then apply the accel load. The output of each accel supply is shown in Fig. 4a, where the step drop in voltage occurs with application of the load, and the 44 μf output capacitor slowly stabilizes. (This and subsequent figures are traces of original plates that were not satisfactory for reproduction; accordingly some detail of the 12-pulse ripple is lost. In other cases, run length did not permit and adequate number of points to detail the ripple.) This is an 80 ms, run where the accels were turned on at 10 ms. Fig. 4b shows the filament output voltage. Previous runs had shown that this voltage stabilizes at the value it had when the accels were turned on. A 2.1% rise in filament voltage is observed after an initial disturbance. This method of system operation was discarded.

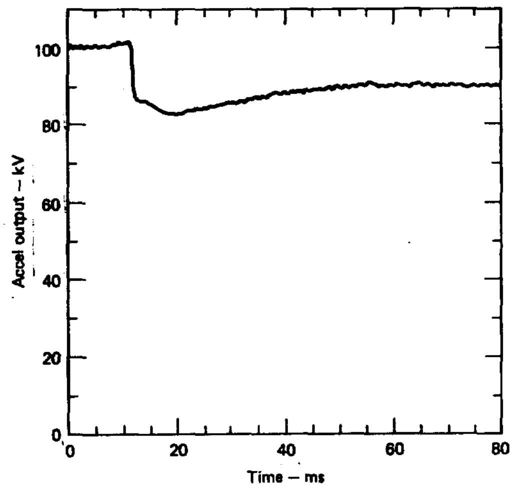

Fig. 4a

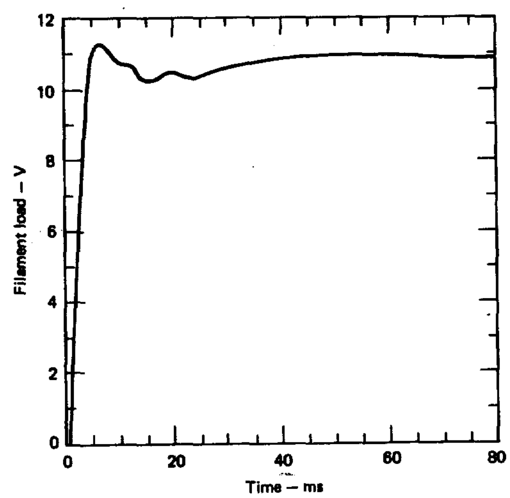

Fig. 4b

TACS Control of Current Sources

A better method of operating the system is to use two tubes in the output: one as a series current source to the load and the other as a shunt current source to be ramped on before the series tube. This method should eliminate perturbations on the filament supply when the ions are being accelerated, since accel current is merely being switched from the shunt to the series tube, and the total accel output current remains at essentially 80 A. This has not yet been simulated, but a ramping current source has been, and its description will be presented.

Shown in Fig. 5 are two electric networks: one is the accel power supply with a single current source output, and the other is a network used to control the current source. The controlling network has an RC time constant of 1 second. The 8585 volts here determines the slope of the voltage vs time on the capacitor, which is very linear for the range desired. The voltage of the capacitor is passed through a type 90 block to the TACS network, where it is input to a static limiter. The maximum output of the limiter is 85, and this value is input to the current source. Hence, for the voltage used, the output current will ramp linearly from 0 to 85 amperes in 50 ms. The output voltage of the accel supply is shown in Fig. 6. Note that the output capacitor has been reduced from 44 to 5 μf. This output is very similar to the results of the Advanced Statistical Analysis Program (ASTAP) used at SRI.

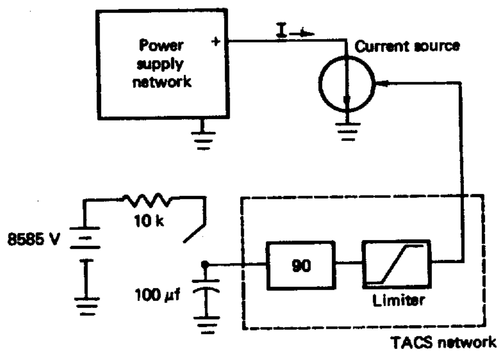

Fig. 5

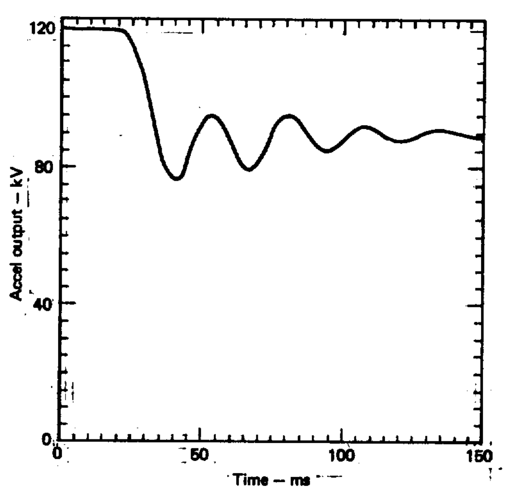

Fig. 6

Although this is a very simple example, it shows how TACS can be used to control a power supply. In the future, TACS will be exploited to model many different problems of the MFTF power supply system.

Harmonic Analysis of Accel Supplies

Circuit Configuration

Of interest is the harmonic content of the current and voltages in the system. A study was performed with a 24 pulse system, scaling impedances to simulate 24 power supplies, as Fig. 7 shows. An 85 A current source was used for each load.

The key to understanding the harmonics in the system is to find those in the secondary of the rectifier transformer; the network configuration toward the ac side determines the pulse number. Vector analysis shows that the 5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th, ... harmonics will be present in each of the six pulse bridges. Because of phase rotation of the two bridges in one supply, the 5th, 7th, 17th and 19th harmonics are eliminated in the 13.8 kV line. Because of the phase shift of the two power supplies, the 11th and 13th are also eliminated, leaving only the 23rd and 25th as the principal harmonics. Of course, this cannot be achieved in the actual circuit because of imbalances and nonlinear elements. However, in comparing the harmonic analysis of a 12 pulse and a 24 pulse system, it is observed that the 11th and 13th are attenuated by a factor of 10.

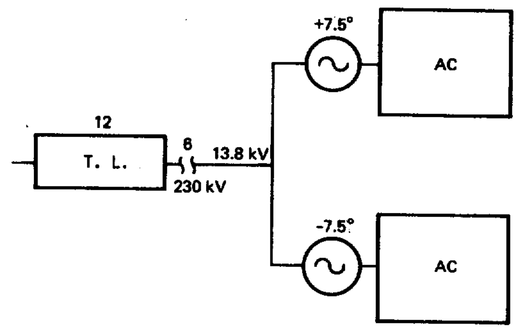

Fig. 7

Angle of Overlap

In analyzing the harmonics, the angle of overlap between adjacent valves is of primary importance. For no overlap, valve currents will have sharp corners, and the transformer secondary line current can be represented as a series of alternating positive and negative pulses. Fourier analysis shows that the magnitude of the harmonic h will be 1/h times the magnitude of the fundamental.

As the overlap between valves increases, the currents lose their sharp corners and appear more sinusoidal. Kimbark[1] has derived formulas to account for overlap that will give the ratio of the harmonic to the fundamental of the valve current. As the angle of overlap increases, the harmonics decrease.

The EMTP output was used as input data for a program written to find the system harmonics. Table 1 lists the results of the simulation, as well as the analytical prediction. The rms fundamental value and dc magnitude are given. The harmonics are given as a percentage of the fundamental. Listed first are the current harmonics in a six-pulse rectifier. The cor-

HARMONICS
(In Percent of Fundamental)

HARMONIC	RECTIFIER XFORMER SEC. CUR.	THEORETICAL	13.8 kV LINE CURRENT	230 kV LINE CURRENT	RECT. XF SEC. V, L-L	13.8 kV VOLTAGE, L-N	230 kV VOLTAGE, L-N
DC (MAG)	2.84		29.8	1.33	40.35	-15.63	-133.6
FUND (RMS)	72.05		735.9	43.87	32420.00	8195.00	132805.0
2	2.14		2.07	2.91	.60	.84	.12
3	.84		.79	1.47	.36	.45	.06
4	.69		.45	1.01	.25	.31	.04
5	16.67	16.88	.30	.78	2.92	.23	.03
7	10.32	10.19	.18	.53	3.46	.16	.02
11	4.22	3.85	.10	.33	7.12	.10	.01
13	2.80	2.36	.08	.28	6.07	.08	.01
17	1.46	1.26	.05	.21	1.35	.07	.01
19	1.06	1.12	.04	.18	1.44	.07	.00
23	.52	.83	.45	.51	3.83	2.03	.36
25	.49	.66	.41	.50	3.71	1.95	.32
% HARMONIC DISTORTION	20.53	20.30	2.39	3.82	11.93	3.04	.51

TABLE 1

relation between the theoretical and the simulation is very good. The second column shows that the 5th, 7th, 17th, and 19th harmonics are removed in the 13.8 kV line current, as predicted. Also removed are the 11th and 13th, because of the $\pm 7.5^{\circ}$ phase shift of the two power supplies. The next column shows the harmonics in the 230 kV line currents.

Also shown in Table 1 are the voltage harmonics at these points in the system. EMTP shows that this relatively stiff system will have a lower total voltage harmonic distortion than current distortion. (See Figs. 8a and 8b for rectifier current and rectifier transformer input voltage, respectively.)

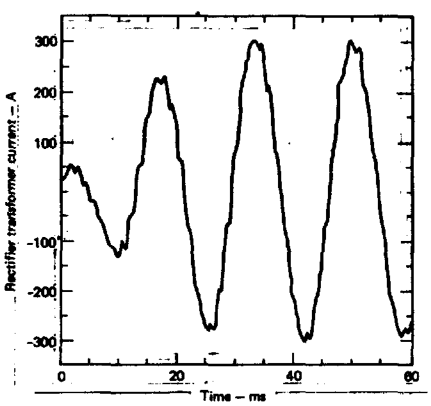

Fig. 8a

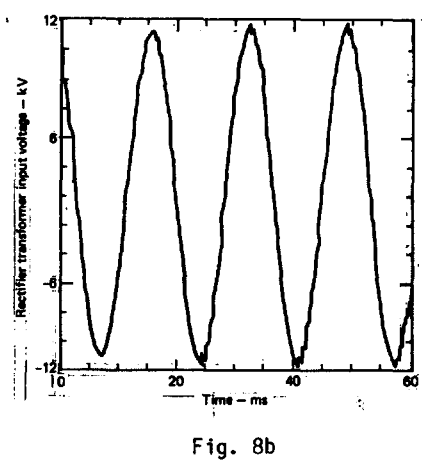

Fig. 8b

Included in the table are some lower order harmonics. Kimbark states that a converter is likely to produce harmonics of all orders, including a dc component. Also, the lower order characteristic harmonics, even though they may be filtered, and the adjacent lower order uncharacteristic harmonics may be large and of the same magnitude. The simulation agrees with Kimbark's claims. The higher orders (26th and greater) are usually ignored and can only be found experimentally.

Forced Phase Retard

A reduction in output voltage can occur in a circuit of two or more six-pulse rectifiers because of a common source impedance.[2] As one diode in a bridge begins to turn on, an adjacent diode that is turning off will not do so immediately, but will remain on for 20-30°, typically 25° for a 12 pulse rectifier. As the dc current is increased, this angle will reach 30°, and the anode to cathode voltage on the other bridge will be delayed, a phenomenon known as forced phase retard. When commutation ends in one bridge, the diode in the other bridge snaps on and -- due to symmetry -- the commutation is exactly 30° long until the current is increased to a value great enough to approach the maximum angle of overlap, which depends upon the ratio of common to total reactance.

To determine if this voltage reduction would be a problem in the MFTF accel supplies, EMTP was used to determine the angle of overlap. For a normal 80 A output, an overlap of 28.0% was found by requesting the program to note all openings and closings of the diodes of interest in the output file. The power factor capacitors in the rectifier transformer secondaries contributed to suppressing forced phase retard.

Accel Crowbar

A simulation of an accel crowbar was modeled on EMTP using two single impedance power supplies and a single-impedance transmission system. Shown in Fig. 9a is a shorted accel output voltage. In this 60 ms run, the crowbar is applied between 15 and 40 ms. Figure 9b shows the output voltage of the unshorted supply, and Fig. 9c is a plot of the 230 kV line current. Figures 9d and 9e show the voltages on the power factor correction capacitors for the unshorted and shorted supplies, respectively. In this case, a 20 kV spark gap was placed across each capacitor. This value has since been increased to 30 kV.

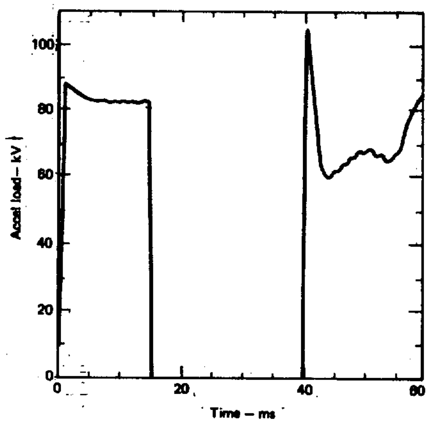

Fig. 9a

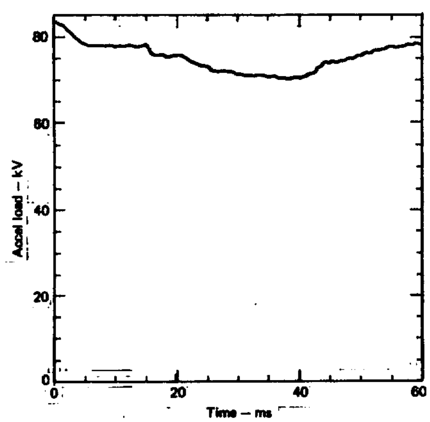

Fig. 9b

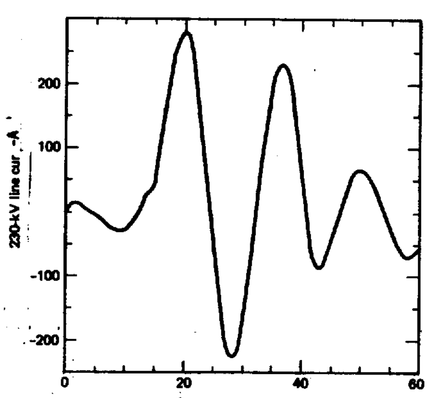

Fig. 9c

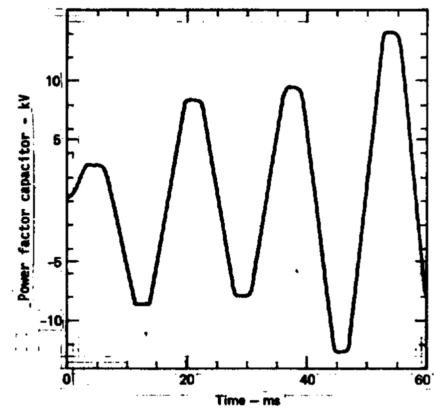

Fig. 9d

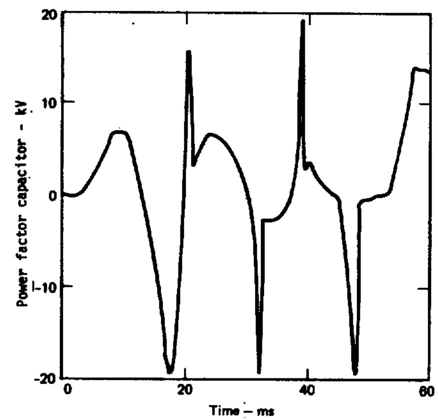

Fig. 9e

Because a crowbar in one supply causes such a large drop in the other, it was decided that an accel crowbar would be a serious enough event to terminate the experimental shot. A crowbar is thought to be a rare event in any case, since the system is designed to crowbar after 20 sparkdowns of the source, and the switch tube subsequently fails to remove source voltage.

Conclusion

EMTP has been used to simulate the MFTF Sustaining Neutral Beam Power Supply System and has pointed to some of the system problem areas. The code has been found to give results similar to those of more prestigious codes. The use of TACS can be a powerful tool in modeling an electric network. The use of EMTP by those who have access to the MFE CRAY computer is encouraged.

References

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2. R. W. Kuenning, "Operation of 12 Phase Rectifier/Consisting of 2 Three Phase, Full Wave Bridges in Series," Lawrence Berkeley Laboratory Engineering Note (1951).

3. Saad H. Amer, "80 kV Power Supply Sustaining Neutral Beam Power Factor and Harmonics," Lawrence Livermore Laboratory (1978).